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Expert System Generated Coral Bleaching Alerts for Myrmidon and Agincourt Reefs, Great Barrier Reef, Australia.

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Abstract An expert system, termed the Coral Reef Early Warning System (CREWS), was employed at NOAA's Atlantic Oceanographic and Meteorological Laboratory (AOML) in Miami, Florida, USA, to provide interpretations of combinations of near real-time meteorological and oceanographic data, thought to be conducive to coral bleaching. These data were collected via HF radio from automatic weather stations operated by the Australian Institute of Marine Science at Myrmidon and Agincourt Reefs in the central Great Barrier Reef. At Myrmidon Reef, CREWS was useful in "predicting" coral during the end of January and early February 2000. This prediction was verified in the field with observations of low level bleaching for a few species of *Acropora* bleaching (especially *Acropora gemmifera* and *A. digitifera*) on the reef flat at Myrmidon Reef. In February 2000, alerts were produced and sent for Agincourt Reef, 330km north of Myrmidon Reef, but field observations showed that bleaching did not occur. These results suggest that CREWS may be fine-tuned to predict bleaching in thermally sensitive species or genera at individual locations.

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Keywords Corals, bleaching, thermal stress, expert systems, Great Barrier Reef.

Introduction

The phenomenon of coral bleaching has received widespread attention in recent years (e.g., see reviews by Glynn 1993, Brown 1997, Hoegh-Guldberg 1999). It is often regarded as a generalized stress response by zooxanthellate organisms such as corals to high sea temperature or abnormal salinity, bacteriological or viral infection, high solar radiation, pollutants and a range of other stressors (Glynn 1993; Brown 1997; Kushmaro et al 1997; Jones 1997). In most reported incidences of mass coral bleaching, however, locally high sea temperature is in evidence and appears to be the chief environmental stressor (Brown & Ogden 1993). One other meteorological variable that is thought to be conducive to bleaching, in the presence of high sea temperatures, is the presence of low wind speed, as this is thought to favor localized heating and a greater penetration of solar radiation (Glynn 1993; Causey 1988; Jaap 1978, 1988; Lang 1988).

Bleaching events of varying intensity occurred on the GBR in early 1980, 1982, 1987, 1992 and 1994 (Oliver 1985; Hoegh-Guldberg et al. 1997). However, the GBR experienced its most intensive and extensive coral bleaching event on record in early 1998, with 25% of inshore reefs being severely affected (Berkelmans and Oliver, 1999). The economic ($2 billion per year) and conservation status of the world-heritage listed GBR militate that a greater understanding of threats like coral bleaching are pursued.

The large extent of the GBR, which comprises over 2500 individual reefs along a stretch of 2000 km, makes monitoring its physical environment difficult at best. The Australian Institute of Marine Science (AIMS) and the Great Barrier Reef Marine Park Authority (GBRMPA) have ambitious programs of monitoring physical, chemical and biological features of the GBR (e.g.Wachenfeld et al. 1998, Sweatman et al. 2000). Correlating physical environmental conditions to environmental disturbances such as coral bleaching is therefore of particular interest as it assists in the monitoring and management of the GBR Marine Park. A network of automatic weather stations operated by AIMS and GBRMPA comprises instruments at Myrmidon Reef, Agincourt Reef, Halftide Rocks, Cleveland Bay, Davies Reef and Hardy Reef and present a particular advantage in that they relay near real-time sea temperature, wind and light data. A system that could monitor these data automatically, look for matching data patterns that are thought to be conducive to coral bleaching, then produce an alert, would have a number of advantages. Firstly, it would enable researchers to travel to the site of coral bleaching and study the developing phenomenon first hand, rather than after the fact. Secondly, it would help public relations in keeping commercial operators on the GBR, politicians and the general public informed; and thirdly, it would help the GBRMPA in ameliorating local-scale human impacts which might exacerbate coral bleaching.

Expert systems, or knowledge-based systems, are a branch of artificial intelligence. Artificial intelligence is the capability of a device such as a computer to perform tasks that would be considered intelligent if they were performed by a human (Mockler & Dologite 1992). An expert system is a computer program that attempts to replicate the reasoning processes of experts and can make decisions and recommendations, or perform tasks, based on user input. Knowledge engineers construct expert systems in cooperation with problem domain experts so that the expert's knowledge is available when the expert

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might not be, and so that the knowledge can be available at all times and in many places, as necessary. The knowledge base upon which the input is matched is generally represented by a series of IF/THEN statements, called production rules, which are written with the domain expert to approximate the expert's reasoning. Conclusions may be represented in fuzzy terms such as "possibly," "probably," or "almost certainly."

The automated methodology we describe here is a data-driven expert system which reviews data collected from Myrmidon Reef and Agincourt Reef, and produces alerts when conditions are thought to be conducive to coral bleaching. This expert system is an extension of the Coral Reef Early Warning System (CREWS) originally implemented for Sombrero Key in the Florida Keys, USA (Hendee 1998a, 1998b). CREWS screens near real-time incoming wind speed, sea temperature and Photosynthetically Active Radiation (PAR) data (among other types) to determine if conditions exceed those which may induce coral bleaching at Myrmidon and Agincourt Reefs.

Methods

The basic structure of the expert system has been previously described in Hendee 1998a and 2000. Production rules utilized in CREWS were drawn from published data on coral bleaching (Berkelmans and Willis 1999), unpublished data from automatic weather stations and field observations, and from discussions in the literature, as cited above and below. CREWS utilizes over 700 permutations of high sea temperatures vs. low wind speeds vs. high PAR vs. time of day in its production rules. More stressful conditions are represented by a higher number of points than less stressful conditions. For a complete description of the algorithms implementing the production rules, please see Hendee 2000, or contact the senior author.

CREWS accepts as input wind speed, PAR and sea temperature derived from the station instruments. Thus, depending on how high the sea temperature was, in combination with low winds and/or high PAR, or how high the sea temperature was without low winds, conditions conducive to a coral bleaching event are described in fuzzy terms through automated "alerts" , broadcast as email messages and via the World-Wide Web early each morning, as one of the following:

Conditions almost certainly favorable for bleaching
Conditions probably favorable for bleaching
Conditions possibly favorable for bleaching

The system is configured so that alerts are only kept for seven days, so that if no new production rules are triggered for a whole week, alerts are no longer sent. At the end of each alert, the number of production rules triggered is calculated and presented to show the basis of the alert.

At Myrmidon and Agincourt Reefs, data are acquired every half hour, then automatically transmitted within a few minutes by HF radio to receiving stations located at AIMS (for Myrmidon Reef) and Port Douglas (for Agincourt Reef). The data are reformatted at AIMS and sent once per day via FTP to a workstation located at AOML. A series of programs at AOML implement the CREWS screening of the data shortly after their scheduled arrival. If any alerts are produced, they are emailed to selected coral researchers and posted to a Web site on the AOML workstation. Any alerts produced are also archived and made accessible via the Web. Thus, researchers and managers are notified as soon as conditions conducive to coral bleaching are met and continue to be notified up to a week afterwards, and the data made available retrospectively via the Web site (http://www.coral.noaa.gov/gbr/es).

To verify whether coral bleaching occurs after the alerts are posted, field trips are made to determine the extent of coral bleaching, if any.

Results

During the last few days of January 2000, coral bleaching alerts were produced for Myrmidon Reef (Figure 1, 2) and Agincourt Reef (Figure 3, 4). A field investigation on 14 February 2000, showed that on the inner reef flat of Myrmidon Reef, there were a large number of partially bleached and a few totally bleached corals. The dominant coral in the area were members of the genus *Acropora*, in particular the *humilis* group and other corymbose growth forms. All colonies that had some partial mortality to their southward facing sides (which occurred in 1997) showed some degree of bleaching or increased host-based fluorescence. About 80% of colonies in the area appeared affected; however, there was no apparent mortality at the time of the visit. Water temperature at the time reached a high of 29.7° C, winds were calm and the sea was relatively flat (Fig 2). During February, bleaching was apparent along a channel on the northern side of the reef (both sides) extending over an area of several hundred meters to one kilometer. Bleaching was only partial and exclusive to a number of species. All *A. gemmifera* appeared to be affected with various degrees of paling or fluorescing. *A. digitifera* was another species which appeared affected while other species in the *humilis* group (*humilis* and *monticulosa*) and other *Acropora* were not effected, with the exception *of A. palmerae,* which had a ring of 5-10 cm band bleached around the margin.

At Agincourt Reef however, daily visits by a tourist operator, Quicksilver Connections, revealed no signs of bleaching (including *A. gemmifera)* at any time during the summer of 2000 despite bleaching alerts being generated. Alarm triggers were set at the same levels for both Agincourt and Myrmidon Reefs.

Discussion

The high sea temperature heuristic for coral bleaching used in the current study states that temperatures over 29.5^{o}C must occur for a whole day before coral bleaching will begin to occur. However, coral bleaching is a complex phenomenon (as rmodeled in the algorithms, which show "points" in Figure 1 as an attempt at model verification), and it is difficult to tell whether high temperature alone, or in combination with high PAR, and/or low winds were contributing factors. The effect of ultraviolet radiation (UV) may play an important role in the bleaching response. Jaap (1978) discussed the apparent contribution of low tides and low winds in more rapid solar heating to induce coral

bleaching at Middle Sambo Reef in the southern part of the Florida Keys, Florida, USA. However, in light of the work of Lesser et al (1990), and of Gleason & Wellington (1993), who presented convincing evidence of the effect of UV in inducing coral bleaching in *Montastrea annularis* within three weeks, irrespective of water temperature, it may be that the effect of low tides is more a result of greater penetration of UV than of solar heating. Also, low winds result in greater water clarity, due to the reduced effect of wave diffraction of light; hence, a greater penetration of UV.

Environmental conditions were very similar on both Myrmidon and Agincourt Reefs during the late January/early February period in 2000 (Figs 2, 4). The alerts at Myrmidon Reef were verified by field observations, but proved to be a false alarm for Agincourt Reef. As the coral species which bleached at Myrmidon Reef are also present at Agincourt Reef, (approximately 330km to the north), these *Acropora* species may have different tolerance levels to bleaching. Similar observations have been made for broad scale analyses of corals growing at different latitudes (Table 6, Hoegh-Guldberg 1999) and may represent evidence of adaptation to thermal stress. However, it is equally possible that these differences are due to the different thermal histories (acclimation). Resolving these differences would require further investigation (e. g. transplant experiments) and is beyond the scope of the current study. Expert system rules are currently being reprogrammed for Agincourt Reef to adjust alarm triggers as a result of this feedback.

Although the alerts and subsequent observations of bleaching at Myrmidon Reef revealed localized and mild bleaching, the early warning system clearly shows potential. Having this advance notice of possible bleaching allowed for a coordinated documentation of bleaching through incidental observations by scientists from a wide range of organizations. Fortunately, the warm water temperatures of late January abated by mid-February, avoiding a more widespread bleaching event.

With the encouraging results from the summer of 2000 and further refinements to the expert system rules, more weather stations are being implemented with the CREWS system to provide a better representation of the GBR. These include inshore sites at Cleveland Bay, near Townsville and Halftide Rocks in the southern GBR, as well as offshore weather stations at Davies and Hardy Reef.

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~~~~ Myrmidon Reef Coral Bleaching Alert for 02/01/2000 ~~~~


Rule-TWP2 (24 points)
Conditions possibly favorable for bleaching on 01/30/2000, because:
  in situ sea temperature was very high (about 29.6) during mid-day,
  and PAR was high (about 1462) during mid-day.

Rule-TW7 (6 points)
Conditions possibly favorable for bleaching afternoon on 01/28/2000 because:
  sea temperature was very high (about 29.6),
  and wind speed was very low (about 5.7) during afternoon
  (PAR not considered).

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High temperature only points:                          0
High temperature, low wind points:                     6
High temperature, low wind, low tide points:           0
High temperature, low wind, high PAR points:           0
High temperature, high PAR points:                    24
High temperature, low wind, high PAR, low tide points:  0

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Total points triggered:                               30
Number of rules triggered:                             2
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Figure 1. Coral bleaching alert for Myrmidon Reef, Summarizing alert message and data from January 28 through February 1, 2000.

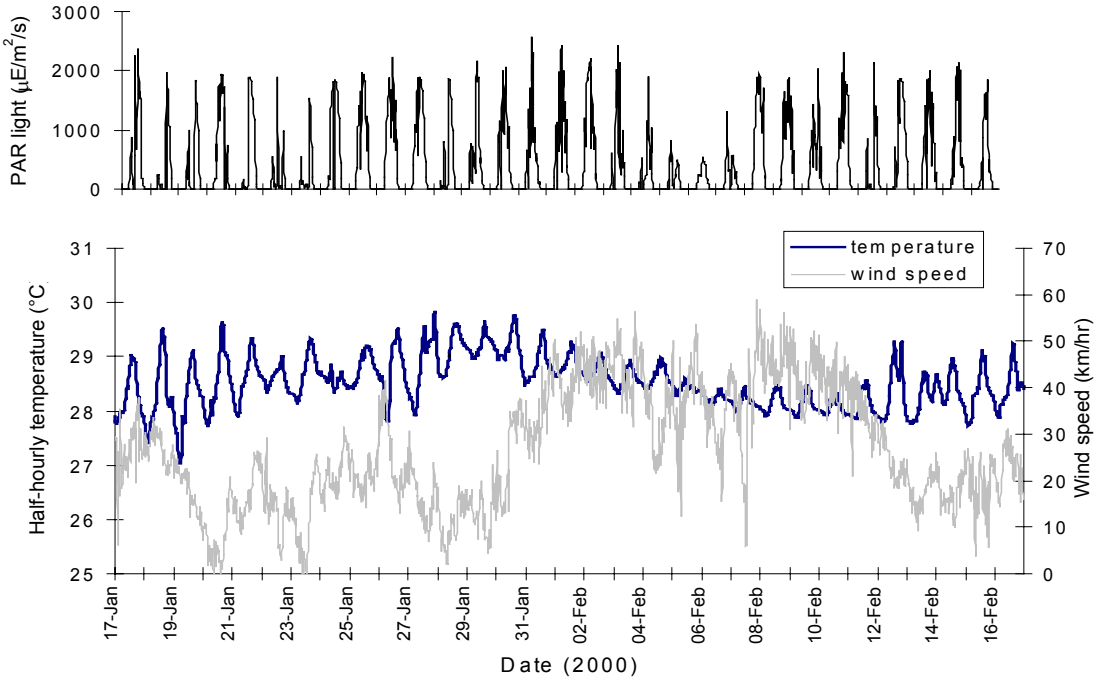

Figure 2. Half-hourly sea temperature (1m), wind speed and PAR light at Myrmidon Reef around the period of the bleaching alerts.